Preprint
UCRL-JC-142244

Relative Advantages of Direct and Indirect Drive for an Inertial Fusion Energy Power Plant Driven by a Diode-Pumped Solid-State Laser

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This article was submitted to the 4th Symposium on the Current Trends in International Fusion Research: A Review, Washington, DC, March 12-16, 2001

U.S. Department of Energy

Lawrence Livermore National Laboratory

March 6, 2001

RELATIVE ADVANTAGES OF DIRECT AND INDIRECT DRIVE FOR AN INERTIAL FUSION ENERGY POWER PLANT DRIVEN BY A DIODE-PUMPED SOLID-STATE LASER*

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ABSTRACT

This paper reviews our current understanding of the relative advantages of direct drive (DD) and indirect drive (ID) for a 1 GWe inertial fusion energy (IFE) power plant driven by a diode-pumped solid-state laser (DPSSL). This comparison is motivated by a recent study (1) that shows that the projected cost of electricity (COE) for DD is actually about the same as that for ID even though the target gain for DD can be much larger. We can therefore no longer assume that DD is the ultimate targeting scenario for IFE, and must begin a more rigorous comparison of these two drive options. The comparison begun here shows that ID may actually end up being preferred, but the uncertainties are still rather large.

1. INTRODUCTION

In the past, it has been difficult to assess the relative advantages of direct drive (DD) and indirect drive (ID) for laser-driven inertial fusion energy (IFE) because of the large uncertainties in the target gain curves and other parameters. New results (1), however, have diminished the importance of these uncertainties. In addition, the demonstration of fusion ignition in the laboratory is approaching a reality in the National Ignition Facility (NIF), so the decision to pursue DD or ID for IFE is becoming increasingly more relevant. For these reasons, we here begin the comparison of the relative advantages of these two drive options for each of the essential systems relevant for a 1-GWe IFE power plant driven by a diode-pumped solid-state laser (DPSSL). We do not treat research items that are not germane to this comparison, and do not by any means suggest that our comparison is either complete or without subjective content. We merely begin the effort of comparing these two drive options. Further experimental studies, especially on the NIF (but also on OMEGA, etc.), as well as more comprehensive theoretical studies, can then be used to fine-tune the comparison to reach a decision as to which drive option should be pursued for IFE.

* *Current Trends in International Fusion Research—Proceedings of the Fourth Symposium*
Edited by Charles D. Orth, Emilio Panarella, and Richard F. Post. NRC Research Press, National Research Council of Canada, Ottawa, ON K1A OR6 Canada, 2001.

2. COMPARISON OF RELATIVE ADVANTAGES

2.1 Target Fabrication

DD has a definite advantage in terms of fabrication complexity because both DD and ID have similar capsule designs, yet ID adds the hohlraum. This added fabrication feature adds significant complexity not only because additional materials are required (perhaps 1/4 g of lead per target), but also because the fabrication assembly process is made more complex by the need to mount the capsule inside a small cylinder. Such complexity will most likely affect the cost per target, and may also enhance chamber activation, depending on the choice of hohlraum material. The activation may affect maintenance procedures, and hence the projected cost of electricity (COE), which is inversely proportional to the fractional time the plant is able to operate (i.e., the availability factor). Activation issues can also affect decommissioning.

If high gain is required for IFE to be economical, a fast-igniter target may be required to avoid the necessity to penetrate a large coronal plasma. Fast-igniter targets may need a cone-like or other asymmetric feature embedded in the capsule to avoid such coronal penetration. With such added capsule complexity, some of the above issues may not be as important as the assembly of such asymmetric targets. This concern is valid for both DD and ID.

2.2 Target Injection

ID has a clear advantage for target injection because ID has a hohlraum that can act as a sabot (thermal isolator) to protect the capsule during injection into a hot high-pressure fusion chamber. The hohlraum can also be "rifled" (i.e., rotated about its axis) to provide stability. A cryogenic DD capsule, on the other hand, cannot survive injection unless the temperature and pressure of the chamber are significantly reduced. An ID hohlraum may also significantly aid target acceleration before injection occurs by providing a metallic "holder" as the object that the accelerator can accelerate. The mounting integrity of the capsule inside the hohlraum is an issue during acceleration, but not a significant one, given the high-gee capability of most mounting schemes.

2.3 Target Tracking and Beam Pointing

ID has a small advantage for target tracking and beam pointing during injection. The hohlraum can serve as a platform upon which glint-producing features can be mounted to aid tracking. Beam pointing requirements are then to a precision equal to something less than the radius of the laser entrance hole (LEH) on the hohlraum, which can be in the millimeter range.

DD tracking is automatically more difficult because the capsule is smaller than the hohlraum, and may not offer any features to aid the tracking equipment. Moreover, beam-pointing precision must be much less than the radius of the capsule to accommodate the "zooming" required for the laser beams to continue to compress the capsule while it implodes. Such zooming is thought to be required for high gain for DD. Even for targets not requiring zooming (i.e., for "tangential" beam focus), greater beam-pointing precision is required than that for ID. A concern for both drives is the consequence of beam energy not going where it should (i.e., hitting the LEH and causing "blowoff" that might close the LEH for an ID target, or missing the edge of a DD target).

2.4 DPSSL Driver

Because of its larger target coupling efficiency, DD has generally been assumed to offer a target gain that is significantly larger than that for ID. People have therefore expected a lower COE for DD, and this has been DD's most attractive feature. Such attractiveness has promoted the perspective that DD is the long-term option of choice for laser-driven IFE, even though most fusion research has been conducted on large machines based primarily on ID (e.g., Nova, Gekko XII).

After it became clear that a DPSSL could be considered as a credible driver for a 1 GWe power plant based on ID (2), investigators realized that the operation of a DPSSL with DD would probably require beams whose intensities would have to be smoothed by some means to remove intensity spikes that can implant perturbations on the ablation surface of a DD target during the early implosion history. These perturbations tend to grow during the implosion of the capsule and disrupt its performance. Beam smoothing is also a concern because wavefront distortion in a DPSSL's gain medium crystals are currently much worse than that for Nd:glass, and such distortions are the primary source of intensity spikes on the beam. We anticipate, however, that refinements in crystal growth procedures may eliminate crystal distortions as a concern for IFE.

The most natural way to smooth the beams for DD, it was thought, was to use some technique like smoothing by spectral dispersion (SSD) (3). By this technique, the injected laser pulse is modulated by temporally shifting its frequency back and forth within the required SSD bandwidth about the peak in the emission line shape. This technique effectively increases the narrow bandwidth of the laser medium so that speckles in a capsule's irradiation can be sufficiently rapidly moved to avoid imprinting the ablation surface.

Imposition of a large SSD bandwidth, however, has a number of effects on the performance of a DPSSL—the amplifier gain is decreased, the B-integral is increased, frequency-conversion efficiency is reduced, and the front-end costs are increased. These effects offset DD's target-gain advantage, even if the target gain for DD at its minimum-COE point is 30% larger than that for ID at its minimum-COE point (1). Consequently, the COE for a DPSSL is the same for DD and ID if we set the B-integral limit constraining the nonlinear growth of intensity spikes on the beam (and hence the threat of optics damage) at 1.8 radians, which is the limit considered "safe" for long-term operation of single-shot Nd:glass lasers.

DD can regain up to a 10% advantage in COE if the following are satisfied:

(1) the fusion chamber can operate at 16% higher repetition frequency;
(2) the diode irradiance can be increased by at least 24%;
(3) either
  (a) the nonlinear growth of beam irregularities (e^{2B}) can be a factor of 2 to 4 higher than is generally accepted as safe, or
  (b) suitable high-average-power spatial-filter pinholes can be developed so that the ΣB constraint (for the whole laser) reverts to a ΔB constraint (between spatial-filter pinholes); and
(4) the above improvements can be implemented at no additional capital cost.

Without these performance enhancements, the COE is essentially independent of the drive mode for the targets at the currently accepted safe limit for avoiding nonlinear optics damage. Therefore, a larger target gain for DD is no longer the attractive feature that it used to be. In addition, there is now some debate whether the target gain for DD is really significantly larger than that for ID.

Complexity of the laser system hence becomes an issue for DD, and complexity usually translates into higher costs or higher scientific risk. Complexity is increased for DD not only because SSD is required for beam smoothing, but also less importantly because the isotropic layout of beams at the fusion chamber requires more optics with a slightly more complicated mounting arrangement.

Specifically, the effective smoothing of speckles on target is actually proportional to the product of the laser bandwidth and the fractional solid angle ($\Delta\Omega/4\pi$) of the laser beams as viewed at the center of the fusion chamber (4). Because beam smoothing is an issue for DD, the realizable ($\Delta\Omega/4\pi$) then becomes an issue. Moreover, to obtain the required laser bandwidth, the laser may require beamlets having four different colors. Treating beamlets with different colors makes the layout of beamlet clusters more complicated. This is especially true when polarization issues must be addressed in treating a pulse shape with both a "foot" and "main" pulse, and when addressing zooming of focus to follow a capsule's implosion.

Note that, because we are making comparisons of DD and ID based on essential IFE systems, it makes no difference that DD may require a smaller laser (e.g., 2.2 MJ instead of 3.7 MJ at 1 GWe). The real systems issue is the COE.

In summary, because the COE is the same for DD and ID, ID has the advantage for the driver because of the added complexity for DD.

2.5 Fusion Chamber

The comparison of DD and ID for the fusion chamber is not clear. ID has a greater shrapnel threat from duds because of the hohlraum, but few duds should be expected! The large cone half-angles (~50°) currently used for ID research must of course be decreased to make ID readily adaptable to liquid first walls that are likely to have larger availability factors. Smaller cone angles, however, decrease the expected target gain. Moreover, the hazard from splash (droplets) interfering with the next shot has not been thoroughly investigated, and may be problematic. The added hohlraum mass also constitutes additional load for the chamber pumping systems.

On the other hand, DD's isotropic arrangement of beams is generally thought to be incompatible with chamber designs having thick liquid walls, so DD will almost surely be forced to use a dry (solid) first wall. DD may also require a larger solid-angle fraction ($\Delta\Omega/4\pi$) in beam ports to accommodate the required beam smoothing, as discussed above. Both the solid nature of the walls and the larger port ($\Delta\Omega/4\pi$) are likely to cause greater design complexity because of larger neutron leakage and hence the potential for greater substructure damage, activation of components, and tritium adsorption (especially if the wall is a carbon compound). A solid wall also requires a larger chamber radius (and maybe cost) to avoid vaporization. There is also some risk of wall damage from beam energy missing a DD target, both in the zooming process and for a dud.

In summary, it appears that ID may have the advantage for the chamber, but the situation is not clear. There are simply too many unresolved issues.

2.6 Final Optics

DD probably has the advantage for final-optics protection systems. DD has less shrapnel threat (no hohlraum), although it does have a larger number of optics to protect. ID, on the other hand, has a greater likelihood of soft x rays, shrapnel, and debris plasma reaching the optics from the heated hohlraum. The soft x rays probably do not constitute a real problem, contrary to some people's concerns, if the radius to the final optics is sufficiently large. There are concepts (gas puffs, etc.) to deal with the plasma threat, but it should be noted that the introduction into the chamber of such noncondensibles will make it more difficult to condense vaporized wall or other materials rapidly, should that be required. ID also has the possibility of small droplets reaching the optics, if a liquid first wall is used. ID also has a greater threat of material condensing on the chamber transparent vacuum interface (i.e., window) because of the larger mass per target and its metallic nature. The larger mass also constitutes a larger threat from in-flight condensation of debris plasma producing small projectiles that can erode surfaces (perhaps even the final optics).

The biggest problem for final optics is that there is no scheme yet proposed for either DD or ID that has complete credibility. Optics protection is still one of the weak areas for laser drivers.

2.7 System Issues and the Development Path

DD requires a much greater materials development program for wall materials that won't activate or structurally degrade in high integrated neutron fluences, but ID requires a much greater fluid-dynamics development program for liquid walls. Thus, the two types of drive are roughly on an equal footing regarding these types of development programs. However, DD does not have sufficiently high target gain by itself to make IFE cost-effective, and DD may not be as amenable to the fast-igniter scheme that might allow sufficiently high gain. The reason for this is that, although the fast igniter can be used for either DD or ID, the interface issues for target alignment (etc.) may favor ID if asymmetric capsules with cone inserts are required. There is some chance, therefore, that DD may not be able to compete with the COE that ID can attain with a fast igniter.

In addition, DD in general requires a higher level of technology and hence complexity, if for no other reason than its requirement for beam smoothing. In addition, however, no one yet knows whether DD targets have the required hydrodynamic stability against Rayleigh-Taylor and Richtmyer-Meshkov instabilities. One could therefore argue that the technical risk for DD is higher, with our current understanding. ID hence has the overall systems advantage because of less complexity and possibly better applicability to the fast igniter.

3. SUMMARY

Based on the above treatment of the essential IFE systems, Table I below lists which drive option is preferred for the given systems. Although further research will be forthcoming, it would appear at this time that ID has the overall advantage. This is a change from the perspective of the past, and it is primarily Ref. (1) that has made the biggest difference. Nevertheless, it is possible that one of the systems may dominate, or that the increased technology base required for DD becomes available at no significant increase in either cost or risk, so a mere count of the number of rows in Table I for each drive option may not be the best way to summarize the results of this comparison.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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Table I Relative Advantages of DPSSL-driven IFE Drive Options *

System	DD	ID	Preferred
Target fabrication	• Simpler (cheaper)	• Hohlraum adds mass, complexity, and cost	DD
Target injection	• Requires lower chamber T and P or increased technology for target to survive thermal load	• Hohlraum can act as a sabot and can be "rifled" for stability • Hohlraum can be the accelerator "holder"	ID
Target tracking and beam pointing	• Bare target harder to track • Requires more precise beam pointing (zooming)	• Hohlraum "glints" can aid tracking • Less stringent beam-pointing requirements	ID
DPSSL Driver (with target gain G)	• Requires beam smoothing, which is complex with 4 colors, polarizations, and zooming • Requires larger G for same COE as for ID, unless have increased technology base • Requires more optics in a more complex layout with larger port ($\Delta\Omega/4\pi$) for isotropic chamber exposures	• Less complex arrangement of fewer optics • Provides same COE as for DD, but at lower G	ID
Fusion Chamber	• Incompatible with liquid walls • Greater potential for dry wall damage from beams missing target • Dry wall with larger port ($\Delta\Omega/4\pi$) increases neutron leakage (activation and substructure damage) and possibly tritium adsorption (lower plant availability factor) • Requires larger chamber radius to avoid vaporization • Greater possibility of wall damage from beams missing target	• Greater shrapnel threat from target "duds" • More adaptable to liquid walls, which may have larger plant availability factor (less down time) • Liquid walls may increase clearing time (via splash, droplets) and are more complex systems • Hohlraums increase pumping load • Small beam cone angles decrease G	ID (?)
Final Optics	• Larger number of optics • Less shrapnel threat • Less threat of condensation on chamber vacuum window	• Greater threat of soft x rays, debris plasma, shrapnel, in-flight condensates, and liquid droplets reaching optics • Greater threat of condensation on chamber vacuum window	DD
System issues and development path	• Unprotected-wall chambers require greater materials development program. • Less adaptable to "fast igniter" • Higher technology base (greater overall technical risk & cost) especially for beam smoothing and maybe for hydro instabilities	• Liquid wall chambers require fluid-dynamics development program • More adaptable to "fast igniter" technology and hence high-gain targets • Requires less complex technology base	ID

* DD = direct drive, ID = indirect drive